CHAPTER - 9

CONCLUSIONS AND SCOPE FOR FURTHER RESEARCH

This research program has been carried out with the following objectives:

1. To study the effect of fin height during condensation of pure saturated steam over single Horizontal Integral Fin (HIF) tubes to find the optimum fin height.

2. To develop a better technique for reducing the condensate flooding at the bottom of the HIF tubes especially for a high surface tension fluid like water and its impact on condensation heat transfer performance.

3. To study the condensate motion and heat transfer over finned surfaces under the combined action of surface tension and gravity forces numerically to understand the phenomenon better.

4. To develop a simple and easy to use correlation to find the condensing-side heat transfer coefficient during condensation of vapour over single HIF tubes.

9.1 MAJOR CONCLUSIONS

The following are the major conclusions obtained from the present investigation:

1. The HIF tubes of 19.0 mm fin root diameter having rectangular fins with fin spacing of 1.5 mm, fin thickness of 1.0 mm and fin heights of 1.0, 2.0, 2.5, 3.0 and 3.5 mm are tested. The optimum fin height during condensation of steam over the HIF tube is found to be 3.0 mm. This tube yielded condensation (heat transfer) coefficient values from 47.1 to 50.8 kW/m²K (based on the tube surface area at fin root diameter) in the ΔT range of 12 to 24 K. This tube has yielded
the highest heat transfer enhancement ratio of 4.35 at $\Delta T_v = 12$ K among the HIF tubes tested.

2. The optimum fin heights reported by earlier investigators for refrigerant application are around 1.5 mm. The larger optimum fin height obtained with steam in the present study suggests that the HIF tubes with larger fin heights can be adopted for steam applications.

3. The present results have indicated that at lower fin heights, the heat transfer enhancement due to surface tension is found to dominate over the fin efficiency effects. Thus, heat transfer coefficient increases with increase in fin height. While at larger fin heights, the opposite appears to be true.

4. By making a narrow longitudinal slot at the tube bottom and by orienting the finned tube little inclined, condensate is found to drain better along the slot axially.

5. HIF tube with a slot width of 1.0 mm and tube inclination of 5° is found to reduce the condensate-flooding angle by about 40 %. The heat transfer measurements for this condition have improved the heat transfer performance by 30 % when compared to a similar finned tube without the bottom slot.

6. The performance of the tube with lower slot width ($w = 1.0$ mm) is found to be better than that for the tubes with wider widths.

7. In the present study, the effect of tube inclination is studied for the HIF tubes with the bottom slot over the range of 0 to 5°. With the increase in tube inclination, flooding angle decreases. Correspondingly, the heat transfer performance is found to increase. The best performance is obtained at the tube inclination of 5°.
8. A totally different condensate drainage patterns have been noticed. The detailed discussion is available at section 5.4 (d). These observations have indicated that it is possible to control the location of the condensate drainage in case of plain and finned tubes if the currently suggested technique is employed. It may reduce the condensate inundation effects significantly in case of tube banks.

9. The currently suggested technique for reducing the condensate flooding is free from all the problems associated with the use of drainage strips that are suggested by earlier investigators.

10. The two-dimensional numerical solution procedure developed is capable of predicting various aspects of condensate flow and heat transfer over fin surfaces which can be extended to develop new fin geometry.

11. The effect of fin tip radius and fin thickness on overall heat transfer process is small. However, fin height is found to have a significant role.

12. Numerical results are obtained by making the gravity force zero while leaving the surface tension force alone to act and vice-versa. Then, these results are compared with the results obtained by allowing both the forces to act simultaneously. It has indicated that the contribution of gravity force is less than 5.0 % in the total heat transfer process when both the forces are simultaneously present, even though the role of gravity force is significant when it acts alone. This comparative study has led to an important conclusion that by replacing the gravity force term ($\rho g d^3$) in the Nusselt equation by the surface tension force term ($\sigma p$), heat transfer process in the unflooded region of the HIF tube can be modeled. It has resulted in a new non-dimensional number \[ \left( \frac{\rho h_{fg}}{\mu k T} \right) \left( \sigma p \right) \] which is named as “Surface tension number” and denoted as “$Su$".
For a given fin dimension, the relative magnitude of average Nusselt numbers obtained with different condensing fluids are found to be in the relative order of the Surface tension numbers. It has consolidated the idea that Surface tension number can be used to correlate the heat transfer contribution of the unflooded tube region.

Using the non-dimensional parameters identified from the numerical study, a model having only four non-dimensional equations has been developed for predicting the heat transfer performance during condensation of vapour on single horizontal integral fin copper tubes with rectangular or trapezoidal fins. The model has six empirical constants that are obtained by correlating the 183 experimental data obtained with 75-tube geometry during condensation of Steam, R-11 and R-113 by various reliable investigations including the present one. The prediction capability of the present correlation based model is verified by taking 392 experimental data points. These data were obtained over 132 HIF tubes covering 7 fluids (including the newly developed Ozone safe refrigerants) by 20 investigations.

9.2 SALIENT FEATURES OF THE PROPOSED MODEL

The salient features of the proposed model are as follows:

1. The model contains only four, simple, non-dimensional equations with six empirical constants. The first one is for estimating the fraction of the tube flooded due to condensate retention. Two others are for calculating the heat transfer contributions of the unflooded and flooded region of the tube. The last one is for summing up both the contributions to get the total heat transfer performance.

2. Unlike previous models (that are iterative and complex), the present one is simple to use. If the tube geometry and the fluid properties are known, the condensation
heat transfer coefficient can be estimated easily from the present model by using a hand calculator.

3. As many as 392 data points (covering 132 tube geometry, 7 fluids and 20 investigations) are taken for testing the prediction capability of the present model. The model predicts 80% of the data within ±15% and 88% of the data within ±20% of the experimental values. This model is the first of its kind reported until recently, covering wide range of tube geometry, working fluids and more number of investigations.

4. Recently, considerable amount of experimental data are reported for the Ozone Safe Refrigerants (R-123 and R-134a) of present importance. Though these experimental data are not included while estimating the correlation constants, the predictions of the present model are in good agreement with the experimental ones. Thus, the use of the present model can be extended safely to new fluids also as long as the value of various parameters used are within the correlation range of the model (reported in Table.8.8).

5. The effect of fin geometry (spacing, thickness and height) on the heat transfer performance predicted by the present model agree well with the experimental observations and is relatively better than the predictions of the earlier models.

6. For all the fluids, the value of optimum fin spacing and fin thickness predicted by the present model agree well with the experimental observations. Though the effect of fin height predicted by the present model is satisfactory, it does not locate the optimum fin height reported experimentally. In fact, none of the existing models (including the present one) are successful in locating the optimum fin height. A better way of incorporating the effect of fin efficiency is to be developed for condensation over HIF tube applications.
7. The predictions of the present model is not satisfactory for the Ethylene Glycol data as the $\Delta T_v$ range of the Glycol data are beyond the correlation range of the present model. Hence, a separate set of correlation constants is developed for Ethylene Glycol applications. The predictions of the present model with those constants are in excellent agreement with the experimental data of Ethylene Glycol.

8. The present model is suitable for single HIF tubes made of copper with rectangular or trapezoidal cross section. As the effect of fin efficiency is not incorporated in the present model, enough care must be exercised while using the present model for the tubes made of low thermal conductivity material.

9.3 SCOPE FOR FURTHER RESEARCH

Considerable scope exists for further investigations in the following areas in order to throw more insight on various aspects of condensation heat transfer enhancement over HIF tubes.

1. As fin height is the parameter of prime importance, the investigations concerned with fin height are only two. One is due to Indulkar and Sukhatme (1992) for R-11 and the present one is for water. The effect of fin height during condensation of other fluids needs to be studied experimentally in order to obtain more experimental data for validating the various models.

2. The existing models are not successful in predicting the experimentally obtained optimum fin heights. Thus, attempts have to be made to improve these models.
3. The present models are suitable for two-dimensional single HIF tubes. These models need to be modified suitably for predicting the condensation over HIF tube banks. For three-dimensional finned tubes, similar models need to be developed.

4. The predictions of the present model are limited to the HIF tubes made of higher thermal conductivity materials like copper. The fin efficiency effects need to be incorporated suitably in order to expand its capability for tubes made of lower thermal conductivity materials.

5. As discussed in chapter-5, the condensate drainage patterns observed has suggested that it is possible to control the condensate drainage mechanism for the HIF tubes having the bottom (longitudinal) slot when kept inclined slightly. Such a mechanism can be effectively used to reduce the condensate inundation effects significantly. Condensate inundation can further be minimized by placing circumferential discs at selected axial locations. Extensive studies need to be done in this regard.

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